# Neutrinoless Double Beta Decay: Low Left-Right Symmetry Scale?

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Experiments in progress may confirm a nonzero neutrinoless double beta decay rate in conflict with the cosmological upper limit on neutrino masses and thus require new physics beyond the Standard Model. A natural candidate is the Left-Right symmetric theory, which led originally to neutrino mass and the seesaw mechanism. In the absence of cancelations of large Dirac Yukawa couplings, we show how such a scenario would require a low scale of Left-Right symmetry breaking roughly below 10 TeV, tantalizingly close to the LHC reach.

If neutrinos were Majorana particles [1], lepton number would be necessarily violated, both in low and high energy processes. The former is exemplified by the neutrinoless double beta decay ($0\nu2\beta$) [2], and the latter through the Keung-Senjanović (KS) [3] production of same-sign charged leptonic pair at colliders. While $0\nu2\beta$ can be mediated by Standard Model (SM) physics augmented with Majorana neutrino masses, the collider analogue cries for new physics. A natural example of such a new physics is provided [3] in the context of Left-Right (LR) symmetric theories [4] with Majorana masses for heavy Right-Handed (RH) neutrinos [5]. Present-day experiments on neutrinoless double beta decay [6] are sensitive to the sub-eV region of neutrino masses. There is even a claim of the observation of $0\nu2\beta$ corresponding to the neutrino masses in the range from 0.2 to 0.6 eV [7].

On the other hand, cosmology is setting an upper limit on the sum of neutrino masses [8], which keeps diminishing [9] and makes the contribution due to light neutrino masses potentially incompatible [10] with [7]. Soon, the Planck satellite will help shed light on this important issue [11] and hopefully establish whether neutrino mass is really too small to account for a positive finding of $0\nu2\beta$.

In view of this, we consider seriously the possibility that new physics may be necessary [12]. Recently, we studied this issue in the context of LR symmetric theories in [13] (for a review see [14]), where we pointed out the deep connection between $0\nu2\beta$ and the KS same-sign leptons at colliders, in the context of the so called type-II seesaw [15]. In that case, both these lepton number violating (LNV) processes are related to lepton flavor violation, since all the RH mixing angles are predicted.

In this note we elaborate on this important connection between low and high energy experiments. We imagine a possible situation where $0\nu2\beta$ is measured and the ordinary neutrino masses can not account for it, as described above. We focus on the minimal LR symmetric model, without any assumption on masses and mixings in the neutrino sector. We discuss all the mediators of the $0\nu2\beta$ decay and analyze the scales in this theory, in particular the masses of the RH gauge boson, the RH neutrinos and the RH doubly charged component of the triplet Higgs. As we will see below, the mass of the RH gauge boson should lie tantalizingly close to the LHC reach, which provides further motivation for the hunt for parity restoration at colliders.

**The Model.** The minimal LR symmetric theory is based on the gauge group $\mathcal{G}_{LR} = SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. Fermions are LR symmetric: $q_{L,R} = (u, d)_{L,R}$ and $\ell_{L,R} = (\nu, e)_{L,R}$ and the gauge couplings are $g_L = g_R \equiv g$.

The Higgs sector consists [5] of the $SU(2)_{L,R}$ triplets $\Delta_{L,R} = (\Delta^{++}, \Delta^+, \Delta^0)_{L,R}$, $\Delta_L \in (3,1,2)$ and $\Delta_R \in (1,3,2)$. The group $\mathcal{G}_{LR}$ is broken down to the Standard Model (SM) gauge group by $\langle\Delta_R\rangle \gg M_W$ and after the SM symmetry breaking, the left-handed triplet develops a tiny $\langle\Delta_L\rangle \ll M_W$. $\langle\Delta_R\rangle$ gives masses not only to the $W_R$ and $Z_R$ gauge bosons but also to the right-handed neutrinos. The symmetric Yukawa couplings of the triplets relevant for our discussion are

$$\mathcal{L}_Y = \frac{1}{2}\ell_L \frac{M_{\nu_L}}{\langle\Delta_L\rangle}\Delta_L\ell_L + \frac{1}{2}\ell_R \frac{M_{\nu_R}}{\langle\Delta_R\rangle}\Delta_R\ell_R + \text{h.c.}, \quad (1)$$

where $M_{\nu_L}$ and $M_{\nu_R}$ are Majorana mass matrices of light and heavy neutrinos. There is also a bi-doublet, which contains the usual SM Higgs doublet and another, heavy flavor changing doublet. For a recent detailed analysis of its phenomenology and limits on its spectrum, see [20]. The bottom line is the lower theoretical limit $m_{W_R} \gtrsim 2.5$ TeV. There are also early experimental limits from LHC, still below it but rapidly catching up [21–23].

The bi-doublet provides the usual charged fermion and Dirac neutrino masses. The Dirac Yukawa couplings for neutrinos could in principle be arbitrarily small, in which case one speaks of the so-called type II seesaw [15]. However, the smaller they are, the more fine-tuning one needs, and it may be desirable to avoid this. The smaller $m_N$ is, the smaller the corresponding Dirac Yukawa couplings have to be. The point is that neutrinos are also coupled to the heavy doublet from the bi-doublet, with Yukawas proportional to the masses of charged leptons. The heavy-light doublet mixing then induces Dirac Yukawas [24], which leads roughly to $m_N \gtrsim 10$ GeV, for $W_R$ in the 1 to 10 TeV region.
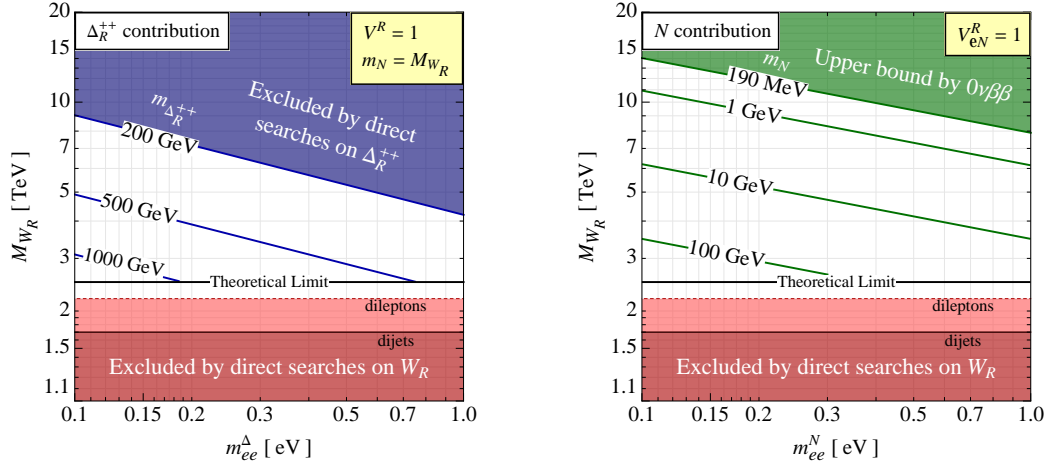
Fig. 1. *Upper bound on $M_{W_R}$ from $0\nu2\beta$ due to the RH doubly charged scalar $\Delta_R^{++}$ (left frame) and to the RH neutrino N (right frame).*

**Neutrinoless double beta decay.** As discussed in the introduction, let us assume that $0\nu2\beta$ decay gets to be observed, while cosmology prevents neutrino masses from doing the job, so that new physics must be its source. In other words, the effective mass parametrizing the $0\nu2\beta$ decay rate should be appreciable: from 0.1 to 1 eV.

The simplest and most popular new physics consists of adding only RH (or sterile) neutrinos to the SM, as to provide neutrino masses through Yukawa coupling with the ordinary LH neutrinos. At first glance these small couplings could not lead to dominant $0\nu2\beta$; this is manifest in the case of a single generation. However in the general case a mild degree of cancelation in the Yukawa couplings could be sufficient to guarantee small neutrino masses while at the same time providing the main source of $0\nu2\beta$ [16–19]. If the RH neutrinos are lighter than about 10 GeV this possibility remains stable in perturbation theory [19], and thus can be considered technically natural. Since such sterile neutrinos can not be observed at colliders, this can be considered as a conspiracy scenario in which one can see $0\nu2\beta$ but not directly the new physics responsible for it. In what follows, we refrain from considering this phenomenological nightmare, and turn instead our attention to the contribution of the Right charged gauge boson.

The main contribution to this process arises from the exchange of RH neutrinos ($N$) or RH doubly charged scalar,[1] which can be measured by the effective mass [13]

$$m_{ee}^N + m_{ee}^\Delta = p^2 \frac{M_W^4}{M_{W_R}^4} V_{Rej}^2 \left[ \frac{m_{N_j}}{p^2 + m_{N_j}^2} + \frac{2\, m_{N_j}}{m_{\Delta_R^{++}}^2} \right], \quad (2)$$

where $p \sim 190$ MeV measures the neutrino virtuality and $V_R$ is the right-handed lepton mixing matrix.

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[1] The joint exchange of both Left and Right gauge bosond plays a minor role. The same is true for the tiny $W_L$-$W_R$ mixing $\xi_{LR} < (M_W/M_{W_R})^2 \lesssim 10^{-3}$ to $10^{-4}$, and for the contribution of the bi-doublet, because of its heavy mass of at least 10 TeV [20].

**Implications for the LR scale.** Let us then ask, what would the LR scenario [34] imply for the scale of the LR symmetry breaking, or more precisely, on the mass of the RH charged gauge boson?

As far as $\Delta_R^{++}$ is concerned, the limit $m_{\Delta_R^{++}} > (110 - 150)$ GeV [25] holds, and was shown recently to be free from the uncertainties which plague the one for $\Delta_L^{++}$ [26]. As a result, the contribution of $\Delta_R^{++}$ can only be dominant for very heavy $N$. The interactions of $\Delta_R^{++}$ are governed by the same $V_R$ that appears in the gauge sector and any off-diagonal entry would mediate lepton flavor violating processes, such as $\mu \to e\bar{e}e$ and $\mu \to e\gamma$. The rates for all these processes are proportional to $m_N/m_{\Delta_R^{++}}$ and in order to be safe from LFV, $V_R$ would have to be nearly diagonal, if $\Delta_R^{++}$ were to dominate the $0\nu2\beta$ rate. Still, in order to contribute to $0\nu2\beta$, $\Delta_R^{++}$ would have to be relatively light and therefore observable at LHC [27]. In such case, the upper bound on $W_R$ mass is depicted in Fig. 1, left frame. The lower bound on $m_{\Delta_R^{++}}$ from direct searches is likely to increase in the near future [36], making this contribution less important.

The contribution of RH neutrinos in turn can be sizable if they are light. However, it is evident from Eq. (2) that the contribution decreases if their mass is lowered below $p \sim 190$ MeV. Therefore, there is an upper limit on the possible contribution to $0\nu2\beta$, and this implies an upper bound on $M_{W_R}$. This is depicted in Fig. 1, right frame, where we chose $V_{eN}^R = 1$, which gives the most conservative upper bound. Even with this extremal choice, we see that the allowed region of $M_{W_R}$ is in the TeV region, where LHC would be able to probe it through same-sign dileptons or leptons plus missing energy.

Notice that this result becomes even stronger if we ask of Dirac Yukawa couplings to be natural, which amounts to $m_N \gtrsim 10$ GeV as discussed above and which would guarantee observing $W_R$ at the LHC for any value of the effective mass that requires an explanation due to new physics.

For experimental probes of the RH neutrino, it is also important the expected range of RH neutrino masses. In this regard, we first point out that $m_{ee}^N$ suffers from an ambiguity, because it can be produced for small ($m_N \ll p$) and large ($m_N \gg p$) RH neutrino mass. Then, we recall that the RH neutrino masses are not completely arbitrary due to cosmological considerations, which we develop in the following section.

***Cosmological constraints.*** If $N$'s decay after the BBN era, they end up destroying the abundance of light elements. This requires $\tau_N \lesssim$ sec, which translates into a lower bound on $m_N$.

Let us first consider the case of the lightest RH neutrino. It turns out that only two regimes are allowed: the *heavy* regime, with $m_N \gtrsim m_\pi + m_\ell$, where $N$ decays sufficiently fast into a charged (anti)lepton and a pion; and a *light* regime, with the lightest neutrino having very low mass $m_N \lesssim$ eV, in which case it is cosmologically stable.

*The heavy regime.* When $m_N \gtrsim m_\pi + m_\ell$, the fastest decay of $N$ is into a pion and a lepton, which has the following decay rate:

$$\Gamma_{N \to \ell \pi} = \frac{G_F^2 |V_{ud}^{qR}|^2 |V_{\ell N}^R|^2 f_\pi^2 m_N^3}{8\pi} \frac{M_W^4}{M_{W_R}^4} \Big[ \left(1 - x_\ell^2\right)^2 -$$
$$x_\pi^2 \left(1 + x_\ell^2\right) \Big] \Big[ \left(1 - (x_\pi + x_\ell)^2\right) \left(1 - (x_\pi - x_\ell)^2\right) \Big]^{\frac{1}{2}}, \quad (3)$$

where $x_{\pi,\ell} = m_{\pi,\ell}/m_N$, $V^R$ is the right-handed lepton mixing matrix, $V^{qR}$ is the analog quark one and $f_\pi = 130 \, \text{MeV}$ is the pion decay constant. We recall that $V_{ud}^{qR} \simeq V_{ud}^{qL} \simeq 0.97$; on the other hand, the leptonic mixing involved depends on the mass hierarchy and on the flavor of the charged lepton into which the RH neutrino is decaying. As one can check from (3), for $m_N > m_\pi + m_\ell$, the above process guarantees that $\tau_N$ is safely shorter than a second.[2]

We can thus summarize the resulting constraints from cosmology as

$$m_N^{\text{lightest}} > 140 \text{ to } 1900 \, \text{MeV}, \quad (4)$$

where the first number is the least constraining ($\ell = e$) and the second is the most constraining in the case when $\ell = \tau$. The actual outcome depends on the unknown mixing angles. Regardless of the mixing angles, below the bound in Eq. (4), there is no process that could make the decay of the lightest $N$ fast enough. There is then only one alternative, which is to go to the *light* regime.

*The light regime and extra species at BBN.* Since for $m_N < 140 \, \text{MeV}$ the lifetime becomes longer than a second, a decaying $N$ would pump too much entropy into the universe. The point is they decouple relativistically at the temperature

$$T_D^N = T_D^\nu \left( \frac{M_{W_R}}{M_W} \right)^{\frac{4}{3}}, \quad (5)$$

where $T_D^\nu \simeq 1 \, \text{MeV}$ is the neutrino decoupling temperature. Therefore, for a representative value of $M_{W_R} \sim 5 \, \text{TeV}$,

$$T_D^N \simeq 250 \, \text{MeV}. \quad (6)$$

Then, since between $T_D^N$ and 1 MeV only muons and pions decouple, at BBN $N$'s are almost equally abundant as light neutrinos. The only way out would be to make $N$ stable and to avoid the over-closure of the universe, lighter than about eV [8, 10, 28].[3] It is easy to check that for such a light neutrino, its lifetime is much longer than the age of the universe. As a result, we are in a scenario where extra species are contributing to BBN. Actually, this situation seems to be preferred and a recent study suggests [30] that four light neutrinos give the best fit to cosmological data, while five is disfavoured and six is basically excluded.

There is an important astrophysical bound on the LR theory with a light $N$ coupled to electrons coming from supernovae cooling [31, 32]. For the minimal LR model with equal left and right quark mixing angles, [33] finds a lower limit $M_{W_R} \gtrsim 23 \, \text{TeV}$ for a small LR gauge boson mixing assumed here.[4] However, this is strongly subject to the right-handed lepton flavor mixing matrix $V_{\ell N}^R$. The $W_R$ can be as light as one wishes, as long as the light $N$ is sufficiently decoupled from the electron; the true limit reads

$$V_{eN}^R \left( \frac{2.3 \, \text{TeV}}{M_{W_R}} \right)^2 < 0.01. \quad (7)$$

This is a rather strong constraint on light RH neutrinos and $W_R$ in the LHC reach, the regime of great interest. For example, the popular type II seesaw scenario where the left and right leptonic mixing angles are the same is ruled out in the case of normal hierarchy, while the inverse hierarchy could work only with a very small $\theta_{13}$, disfavored by recent measurements.

It is also interesting to note that while $N^{\text{lightest}}$ escapes the cosmological bounds (4) by being very light, the heavier RH neutrinos still have to be heavy enough to be BBN safe. The relevant process here is $N^{\text{heavy}}$ decaying to the lightest $N$ and two charged leptons via $W_R$,

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[2] There is also potentially the process $N \to \ell \ell \nu$, mediated through Dirac Yukawas or the LR gauge boson mixing $\xi_{LR}$; but in order to be fast enough it would require either large Dirac Yukawa couplings or large $\xi_{LR}$, both not expected and requiring some degree of cancellation in the lepton or in the quark sector respectively [20].

[3] It is worth mentioning a potential loophole in this argument. The stable neutrino could in principle be heavier, if its abundance were diluted by decays of other species, before the onset of BBN. This scenario was studied in [29], where the authors concluded that $M_{W_R} \gtrsim 10 \, \text{TeV}$ for this to work. In this case, the second RH $N$ has to be heavier than a few GeV and thus $0\nu 2\beta$ decay can never be dominated by new physics.

[4] Reference [33] also finds a light $W_R$ region of about 500 GeV, today excluded by experiments, in the case of the minimal model.
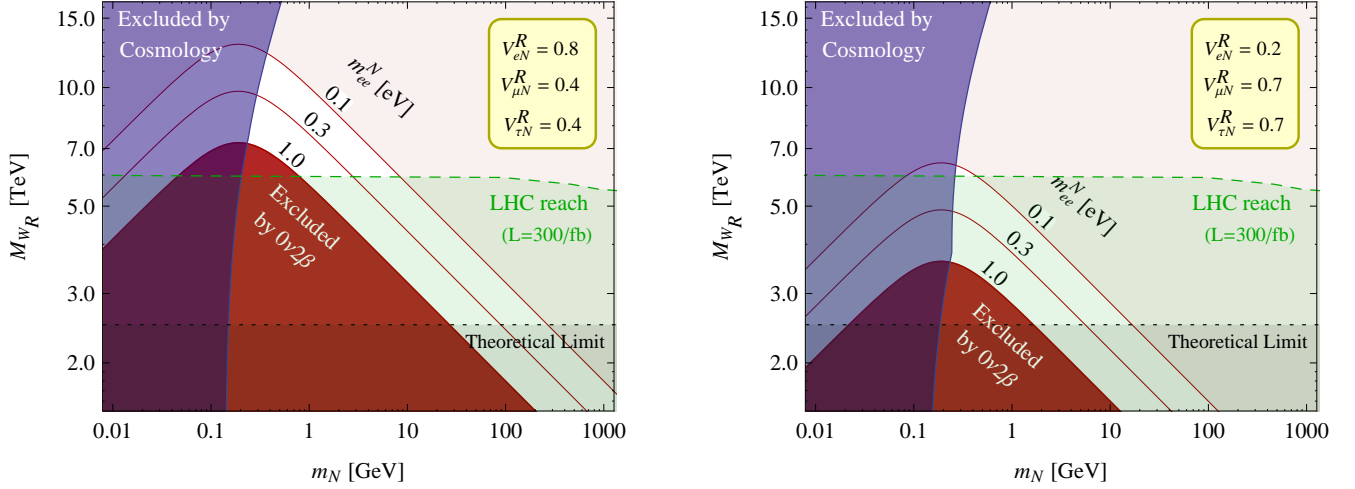
Fig. 2. *Contours of $m_{ee}^N$ in the $(M_{W_R}, m_N)$ plane, illustrated for large (left) and small (right) coupling to the electron $V_{eN}^R$.*

whose decay width is

$$\Gamma_{N_i \to N_j \ell\ell'} = 2\Gamma_\mu \left(\frac{M_W}{M_{W_R}}\right)^4 \left(\frac{m_N}{m_\mu}\right)^5 \left|V_{\ell i}^R V_{\ell' j}^{R*} + V_{\ell j}^R V_{\ell' i}^{R*}\right|^2. \quad (8)$$

This gives a bound on the heavier neutrino mass

$$m_N^{\text{heavy}} \gtrsim 100 \, \text{MeV} \left(\frac{M_{W_R}}{2.26 \, \text{TeV}}\right)^{4/5} \quad \text{to } (m_\mu + m_\tau), \quad (9)$$

which also depends on the mixings; e.g. the higher end refers to the $\mu\tau$ channel.

***Interplay with LHC.*** Let us start with the canonical, SM-like scenario at low energies: only three light neutrinos below eV. In such a case, the limit on the mass of the lightest $N$ given in (4) applies. The cosmological limit is actually dependent on the mass of $W_R$, and its interplay with $0\nu2\beta$ is shown in Fig. 2, illustrated in the case of large and small electron mixing.

The first result to be noticed is that of the two solutions with smaller and larger $m_N$, the cosmological considerations allow only the heavy $N$ solution. This is also welcome in view of the possibility to detect RH neutrinos at LHC, since a light $N$ would decay out of the detector and only manifest itself as missing energy. The second observation is that the values of $m_N$ and $M_{W_R}$ required for $0\nu2\beta$ lie in the region where LHC will be able to probe them through same-sign dileptons or lepton plus missing energy [35].

In the scenario where one or more $N$'s in the light regime play the role of extra light species at BBN, the heavier $N$ still have to satisfy the cosmological constraint given in (9). As a result, a similar situation regarding $W_R$

emerges. If $n_{\text{BBN}} = 4$, basically the same analysis goes through as above. On the other hand, if $n_{\text{BBN}} = 5$ turned out to be the preferred option, one would have a clear prediction. Namely, since the two light $N$'s would have to decouple from the electron due to the SN constraint, the heavy $N$ would couple maximally and the left diagram in the Fig. 2 would apply.

***Discussion and outlook.*** Cosmology keeps lowering the limit on the sum of neutrino masses, which may soon come to clash with possible evidence of $0\nu2\beta$. If so, new physics would be mandatory. This new physics could just be RH neutrinos, assuming cancelations among Dirac Yukawa couplings. In this work we try to avoid this scenario, which leads us to consider the contribution of new RH gauge interactions. In the context of the LR symmetric model, we show how the mass of the RH charged gauge boson has to be less than about 10 TeV, thus very close to the 14 TeV LHC reach with a high luminosity. Another important conclusion which emerges from cosmological considerations is that only the heavy ($m_N \gg 100 \, \text{MeV}$) contribution to $0\nu2\beta$ is allowed, therefore a measurement of the double beta process would relate unambiguously the masses of $N$ and $W_R$.

The situation is particularly exciting in view of the simultaneous time scale for low energy experiments such as $0\nu2\beta$ and LFV, the expected results from the Planck satellite and of course at high energies from the LHC.

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